

## **“Optimizing Observations of Sea Ice Thickness and Snow Depth in the Arctic”**

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### **LONG-TERM GOALS**

This work is motivated by the desire to improve the quality of airborne and satellite-based measurements of sea ice thickness and snow depth in the Arctic; to achieve a resolution that is adequate for monitoring decadal variability and to minimize the degree of uncertainty in predictive models.

### **OBJECTIVES**

The specific objectives are:

- To carefully assess remotely-based observations of Arctic sea ice thickness and snow depth using a rare set of coordinated in situ, airborne, satellite and submarine measurements collected by US Army Corps of Engineering Cold Region Research and Engineering Laboratory (CRREL), Naval Research Laboratory (NRL) and National Aeronautics and Space Administration (NASA) in conjunction with the US Navy at the ICEX2011 sea ice field camp in March 2011 in the Alaskan Beaufort Sea;
- To leverage and integrate the measurements and results from this focused effort with data collected during related national and international activities (e.g. other NASA IceBridge sea ice missions, NRL under flights of CryoSat-2, European Space Agency (ESA) CryoVEx, submarine ice draft measurements, Alfred Wagner Institute (AWI) POLAR5) and historic ICESat records;
- To use these data to revise error estimates of remotely-derived snow depth and thickness data products from, for example, ICESat, IceBridge and CryoSat-2. These error estimates (a) are critical for understanding the variability and trends in the long-term time series of

observations, (b) will help tie the various satellite and airborne records together, and (c) provide important input for predictive sea ice models.

## APPROACH

The paramount transformative aspect of this work is the combined application of coincident ice thickness and snow depth measurements collected in March 2011 [Gardner *et al.*, 2012]. The suite of measurements was strategically organized around a 9-km-long survey line that covered a wide range of ice types, including refrozen leads, deformed and undeformed first year ice and multiyear ice. The data set consists of coincident in situ field measurements of snow depth and ice thickness taken by the CRREL/NRL field team and airborne laser altimetry measurements of the surface elevation of the snow or ice/air interface, and radar altimetry measurements of the snow/ice interface, taken by NASA IceBridge and NRL airborne teams [Gardner *et al.*, 2012]. This suite of data provides the full spectrum of spatial sampling resolution from satellite, to airborne, to ground-based, and will allow for a careful determination of snow depth on sea ice and sea ice thickness distributions. We have augmented the ICEX 2011 in situ measurement with additional airborne and in situ data gathered during the European Space Agency's CryoVex 2011 on thick, multi-year sea ice in the Lincoln Sea, to conduct an assessment of how airborne and satellite altimeter estimates are affected by deformed sea ice surfaces.

***Our culminating objective is to use results from the comparative assessment of these data to revise error estimates of remote snow depth and thickness data products, as a function of ice type.*** The NASA airborne data consists of raw radar echograms from a snow radar, laser altimetry for surface topography and elevation, and visible digital photography for surface morphology. The primary in situ data comprise snow depth and sea ice thickness measurements. We initially concentrate on the issue of deriving accurate snow depth on sea ice, since snow depth uncertainty remains the largest source of error in deriving sea ice thickness from airborne/satellite altimeters. The outcome of the snow depth assessment can be directly applied to revise the airborne estimates of sea ice thickness. Advancements from this work will reduce the level of uncertainty in the observational records of sea ice trends and variability and, hence, increase our understanding of the complex interaction between the atmosphere, ice and ocean in the Arctic region. It will also help us to tie the ICESat, ICESat-2 and CryoSat-2 records together to provide a long-term time series, improving a critical resource for predictive sea ice models.

## WORK COMPLETED

A comparative analysis of the data collected during the March 2011 field campaign in conjunction with ICEX2011 was the focus of Year 1, while in Year 2 the focus was an analysis of related NASA IceBridge (e.g. sea ice flights) data collected during other elements of the March and April 2011 campaign. A journal paper highlighting the analysis was completed and submitted for publication in Year 3, and was successfully published during the no cost extension period of the project, in Year 4 [Newman *et al.*, 2014a]. Additional work during Year 3 included finalizing the ICEX2011 in situ data set for archiving at the National Snow and Ice Data Center (NSDIC). These data are now publicly available for use by the community: <https://nsidc.org/data/icebridge/icex2011-ice-camp.html>. Newman *et al.* [2014a] found that the airborne snow radar data required reprocessing to remove the impact of radar sidelobes on the snow depth estimates (Figure 1). During the no cost extension in Year 4, the project team worked closely with the Center for Remote Sensing of Ice Sheets (CReSIS) at the University of Kansas, providing support in determining reliable methods for coherent noise removal

and deconvolution of snow radar echograms. Following reprocessing by CReSIS, the project team performed a thorough quality assessment of over 16,000 snow radar echograms collected during the NASA Operation IceBridge Arctic campaigns between 2009 and 2012. The reprocessed data provided an improvement over the initial data version and can be used for a more reliable derivation of snow depth on Arctic sea ice (Figure 2). The revised airborne snow radar data will be archived at the NSIDC for wider use by the cryosphere community. Results of our work have been presented in three AGU Fall Meeting presentations in Years 1, 2 and 3. The list of work completed, following the proposed milestones and timeline (referenced to March 2012, project commencement):

- 12 months (Mar 2011): Sea ice field experiment at the ICEX 2011 Beaufort Sea ice camp. Acquisition of in situ, airborne and satellite data (Contributing parties: CRREL, NRL, NASA)
- 1 month (Feb 2012): Publish EOS Brief [*Gardner et al., 2012*] describing coordinated field campaign, conducted near the ICEX2011 Beaufort Sea ice camp (CRREL, U Maryland, NRL)
- + 0 months (Mar 2012): Initial assessment of field data (CRREL, U Maryland, NRL)
- + 6 months (Sept 2012): Synthesis of in situ, IceBridge and NRL airborne data sets collected during ice camp with preliminary data analysis. Generate maps of ice thickness and snow depth for ice camp survey region. (CRREL, U Maryland, NRL)
- + 6 months (Sept 2012): Complete initial report on ice camp activities to include a full description of in situ data collected and success of field campaign. Details reported to ONR Arctic and Global Prediction Program Office. (CRREL, U Maryland)
- + 9 months (Dec 2012): Attendance at AGU Fall Meeting to present results [*Newman et al., 2012*] and meet with international collaborators, laying the groundwork for Years 2 and 3 including data synthesis and coordination of future collaborative field programs (e.g. CryoVEx, AWI POLAR5). (U Maryland)
- +16 months (July 2013): Conduct detailed comparative analysis of CryoSat-2 data with in situ and airborne data to assess the accuracy and precision of CryoSat-2 Arctic sea ice elevation, sea ice freeboard, and derived thickness. Initial work focused on simulation of the CryoSat-2 response in areas of level and ridged sea ice. (U Maryland, CRREL)
- + 18 months (Sept 2013): Continue analysis of combined NASA Icebridge Arctic 2011 campaign and provide report to ONR Arctic and Global Prediction Program Office. (U Maryland, CRREL)
- + 21 months (Dec 2013): Attendance at AGU Fall Meeting to present results [*Farrell et al., 2013*] and meet with international colleagues to continue collaboration on data synthesis and coordination of future field programs. (U Maryland)
- + 22 months (Jan 2014): Meet with colleagues from ESA and NRL to consider implications of analysis in the design of March 2014 field program (CRREL, U. Maryland, NRL, ESA)
- + 28 months (July 2014): Prepare and submit publication [*Newman et al., 2014*]. (UMD, CRREL)
- + 30 months (Sept 2014): Release ICEX2011 in situ snow and ice thickness data to NSIDC, for posting on NASA IceBridge website. (CRREL)
- + 30 months (Sept 2014): Invitation to attend NASA-sponsored snow thickness on sea ice workshop, presenting results of analysis (U Maryland, CRREL)
- + 30 months (Sept 2014): Complete analysis of combined NASA Icebridge and NRL Arctic 2011 data and provide report to ONR Arctic and Global Prediction Program Office. (CRREL, U Maryland)

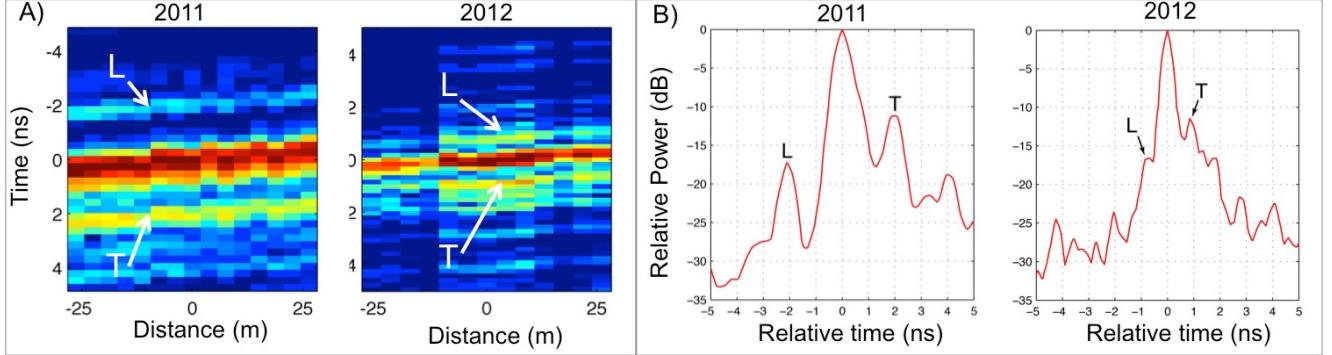
- + 33 months (Dec 2014): Attendance at the AGU Fall Meeting 2014 to present project results, focusing on analysis of airborne snow radar data and validation using in situ measurements collected at ICEX 2011, Bromex 2012 and CryoVex 2011 [Newman *et al.*, 2014b]. (U Maryland, CRREL)
- + 33 months (Dec 2014): Publication of project results in *Newman et al.* [2014a]. (UMD, CRREL)
- + 34 months (January 2015): Completed initial analysis of reprocessed 2011 data and submitted report to CReSIS and NASA IceBridge project [Newman *et al.*, 2015]. (U Maryland, CRREL)
- + 35 months (February 2015): Invitation to participate in the National Center for Atmospheric Research (NCAR) “Snow on Sea Ice Processes Workshop” to discuss novel remote sensing techniques for measuring snow depth on sea ice [Farrell *et al.*, 2015]. (U Maryland).
- + 36 months (March 2015): Commencement of one-year no cost extension (NCE).
- + 39 months (June 2015): Invitation to attend second NASA-sponsored snow thickness on sea ice workshop, presenting results of data reprocessing and analysis (U Maryland, CRREL)
- + 42 months (Sept 2015): Completed analysis of reprocessed airborne snow radar echograms collected during the IceBridge 2009-2012 Arctic spring campaigns. Report provided to CReSIS and the NASA IceBridge project (U Maryland)
- + 43 months (Oct 2015): Provide report to ONR Arctic and Global Prediction Program Office. (CRREL, U Maryland)

## RESULTS

One of the major objectives of this study is to carefully assess observations of Arctic sea ice thickness and snow depth using a set of coordinated in situ, airborne and satellite data sets. During the course of this project we have developed a robust methodology to derive snow depth from airborne snow radar data. We developed a novel wavelet technique and applied this to both IceBridge snow radar echograms [Newman *et al.*, 2014a] and to NRL airborne snow radar data collected in 2014 and 2015 during the DISTANCE project. We assessed the accuracy of remotely-sensed snow depths across a range of ice types, using multiple in situ calibration/validation experiments, across multiple years [Newman *et al.*, 2014b]. *Newman et al.* [2014a] compared the snow depths for the 2011 and 2012 IceBridge campaigns, gathered across the western Arctic, with the snow measurements described in *Warren et al.* [1999]. Snow depth results agreed in areas that continue to contain a high proportion of multi-year ice (MYI), such as north of Greenland and Ellesmere Island. Over much of the Beaufort Sea, Canada Basin and central Arctic we find that the airborne snow depth measurements are up to 60% of those reported in *Warren et al.* [1999]. These regions were previously dominated by MYI during the in situ measurement period (1954-91), but are now dominated by a seasonal ice cover.

The wavelet-based technique developed in *Newman et al.* [2014a] is used to identify the primary reflecting interfaces within the snow pack, from which snow depth estimates are derived. Data from NASA’s IceBridge radar system, which has been making yearly surveys of the western Arctic since 2009, offers a key resource for investigating the contemporary snow cover on sea ice. However sidelobes in IceBridge airborne snow radar echograms impact data collected over sea ice. Based on assessments completed during this project we notified the instrument teams of artifacts and deficiencies in both the IceBridge and NRL snow radar datasets, that required each to be reprocessed. These sidelobes can have a similar appearance to actual snow layers leading to ambiguity in detection (Figure 1a). We characterized the IceBridge snow radar instrument response to ascertain the location

of side-lobes, aiding the interpretation of snow radar data (Figure 1b). The project team worked closely with the instrument teams, providing assistance to determine reliable methods for coherent noise removal and deconvolution of snow radar echograms. Following reprocessing by CReSIS, the project team performed a thorough quality assessment of over 16,000 snow radar echograms, covering over 80,000 km of sea ice, collected during the IceBridge Arctic campaigns between 2009 and 2012.

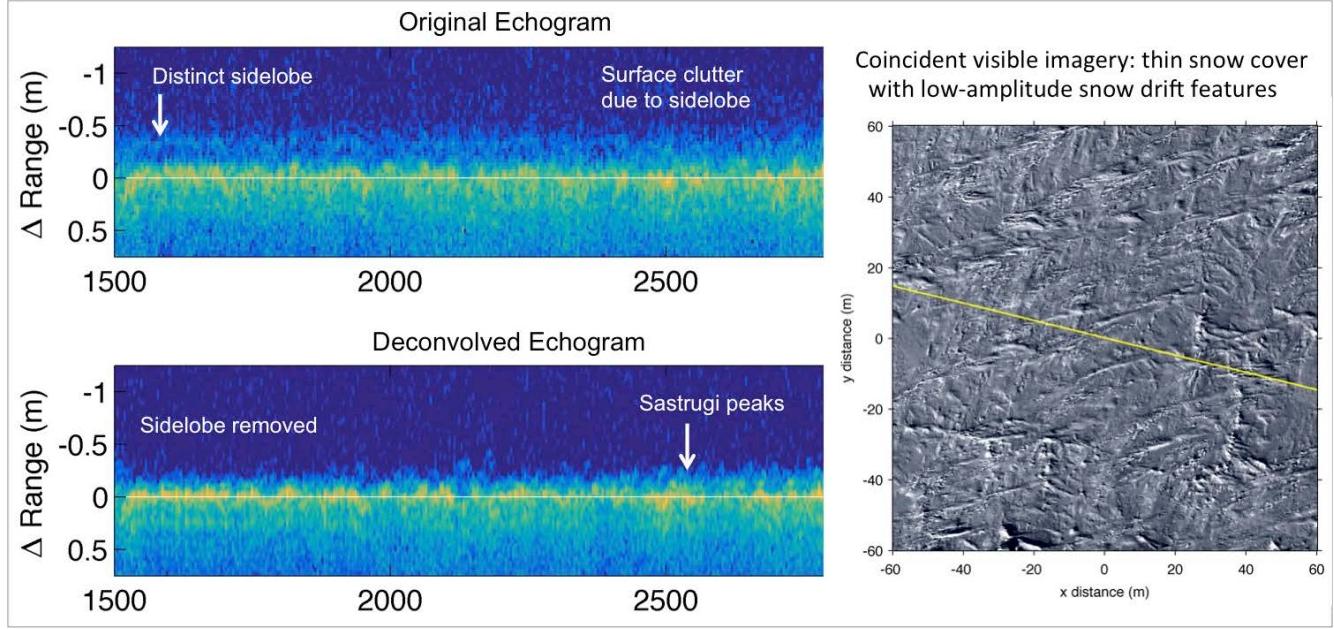


**Figure 1:** (A) Sidelobes in airborne snow radar echograms from the 2011 and 2012 IceBridge missions over sea ice. Sidelobes can have a similar appearance to actual snow layers leading to ambiguity in detection. (B) Average of 690 (2011) and 295 (2012) snow radar waveforms collected during “ramp-pass” surveys over the Thule and Kangerlussuaq airfields. ‘L’ and ‘T’ indicate the main leading- and trailing-edge sidelobes in the snow radar waveforms. Adapted from Newman et al., 2014.

We assessed the newly reprocessed remote sensing radar using the novel wavelet algorithm and conducted comparisons with in situ data collected on sea ice in the Beaufort Sea at the ICEX 2011 camp. We demonstrated that the reprocessed airborne snow radar data offers a significant improvement over the original data, after the removal of artifacts due to sidelobes and coherent noise (Figure 2). The reprocessed data allows snow features to be identified and a more accurate derivation of snow depth. For snow on undeformed first-year ice (FYI) at ICEX 2011 we found that airborne estimates agreed with in situ measurement to within 1 cm in mean, modal and median snow depth, while over deformed FYI the agreement was within 3 cm in mean, modal and median snow depth. Over undulating MYI, with thin snow cover, there is a tendency for the airborne snow radar to overestimate snow depth due to misinterpretation of the morphology associated with old, melt-pond features.

Radar returns from altimeters are impacted by the morphology of snow and ice features on the surface, as well as the characteristics of radar pulse penetration through the snow pack. Newman et al. [2014a] found a limitation in the utility of a one-dimensional in situ survey line for assessing the uncertainty of satellite and airborne snow radar measurements, since radar retruns can arise from off-nadir. The project team recommended that future field surveys designed to test the accuracy of airborne snow or ice thickness estimates be comprised of a two-dimensional grid layout that captures both the along-track and across-track variability within the footprint of the remote sensing instruments. This improvement to in situ survey design was implemented in the March 2014 sea ice field campaigns at multiple measurement locations in the western Arctic Ocean that were supported by ESA, NRL, NASA, and ONR. The full effect of surface morphology on the snow radar may now be investigated using a nested approach that includes forward modeling, snow radar data and a comprehensive set of 2-D gridded in situ measurements. This will allow us to better constrain the altimetric uncertainty

resulting from ice surface morphology, with respect to ice type. This will lead to an enhanced understanding of sources of uncertainty in altimeter-derived sea ice thickness products.



**Figure 2:** (left) Segments of a snow radar echogram along the ICEX 2011 survey line before (“original echogram”) and after (“deconvolved echogram”) the application of techniques to remove coherent noise and deconvolution to remove leading- and trailing-edge sidelobes. Increased signal to noise in the final echogram allows for easier identification of the snow layer and snow features such as sastrugi. (right) Coincident aerial photograph from the Digital Mapping System (DMS) indicates an ice floe with thin ice and distinct snow morphology. IceBridge flight-line is indicated by yellow line.

## IMPACT/APPLICATIONS

Data collected at the ICEX 2011 ice camp included measurements of undeformed and deformed first year ice and multiyear ice. Consistent with the work of Farrell *et al.* (2012), our investigation revealed differences, especially in accuracy, from several of the instruments as a function of ice type. Interpretation of radar data is particularly challenging over deformed ice. The revised error estimates of remotely-sensed snow depth and ice thickness observations generated by this investigation are critical for (1) understanding variability and trends in the long-term time series of NASA IceBridge observations, (2) tying the ICESat, ICESat-2 and CryoSat-2 records together, and (3) providing important input for predictive ice models. Moreover the comparative study between the in situ data sets and coincident airborne and satellite data acquisitions has improved understanding of these new sensors, including the University Kansas/CReSIS snow radar, the NRL radar altimeter, and CryoSat-2’s SIRAL radar altimeter. This knowledge is now being applied to aid in the analysis of the entire NASA IceBridge sea ice data set, including a re-evaluation of the level of uncertainty in snow depth and ice thickness estimates. Using the results from this project as a springboard, future work should include a comparison of the results from the recently reprocessed airborne snow radar data with in situ measurements gathered at a range of locations across the Arctic in 2014. This will allow the improved

accuracy and quality of the snow radar remote sensing data for to be tracked and useful for Arctic snow depth investigations.

Incorporating knowledge of these measurements and their accuracy into new algorithms will support improvements in regional sea ice models. The results will influence future sensor, and sensor suite, development and provide a metric for combining/contrasting future dataset collections. They also affect the design of current and future field collection strategies, particularly the implementation of two dimensional in situ measurement grids aimed at improved coupling between in situ, airborne and satellite observations.

## RELATED PROJECTS

- **NOAA:** “Towards Operational Arctic Snow and Sea ice Thickness Products” is supported under the NOAA/NESDIS/STAR/SOCD Ocean Remote Sensing Program and is conducted in collaboration with NASA IceBridge and CRREL. It continues to support the collection and reduction of a long-term time series of snow and sea ice thickness data in the Arctic Ocean. The goal is to continue the legacy of previous Arctic airborne campaigns conducted since 2002 to gather high-resolution altimetry over both seasonal and multiyear ice floes. These high-resolution datasets are used as a calibration and validation tool to assess accuracy of satellite altimeter measurements (Envisat, ICESat and CryoSat-2) over sea ice.
- **NASA IceBridge** ([www.nasa.gov/mission\\_pages/icebridge](http://www.nasa.gov/mission_pages/icebridge)): The NASA IceBridge project is closely related to this ONR work, including an airborne survey over the 9-km ground line used to collect in situ snow and ice thickness data at the ICEX2011 field camp. The goal of IceBridge is to utilize a highly specialized fleet of instrumented research aircraft to characterize annual changes in the thickness of sea ice, glaciers, and ice sheets. IceBridge bridges the gap in observations between NASA's ICESat satellite missions.
- **NRL:** “ Determining the Impact of Sea Ice Thickness on the Arctic’s Naturally Changing Environment (DISTANCE)”. DISTANCE is providing direct support for a key element of our collaborative team, responsible for processing and analyzing the airborne data collected by NRL. The objective of DISTANCE is to understand the changing Arctic environment using new techniques for deriving accurate multi-sensor snow and ice thickness information and coupled ice-ocean models to explore the new Arctic dynamics. The goal is to provide the Navy with an improved forecast capability that accurately describes Arctic change, and new global fields of snow and ice thickness for data assimilation.

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